NUCLEAR PHYSICS 12

→ GOLDSTONE THEOREM

→ CHIRAL SYMMETRY

$\boxed{\text{RECAP}}$ We studied the $\boxed{\text{LINEAR SIGMA MODEL (L}\sigma\text{M)}}$

→ Problem addressed by LσM:

$\boxed{\text{Why is the pion so light?}}$

$$\frac{m_\pi}{m_\rho} \sim \frac{1}{5}$$

$$\frac{m_\pi}{m_N} \sim \frac{1}{7}$$

$\boxed{L\sigma M}$

1) Theory w/ massless nucleons & massive bosons

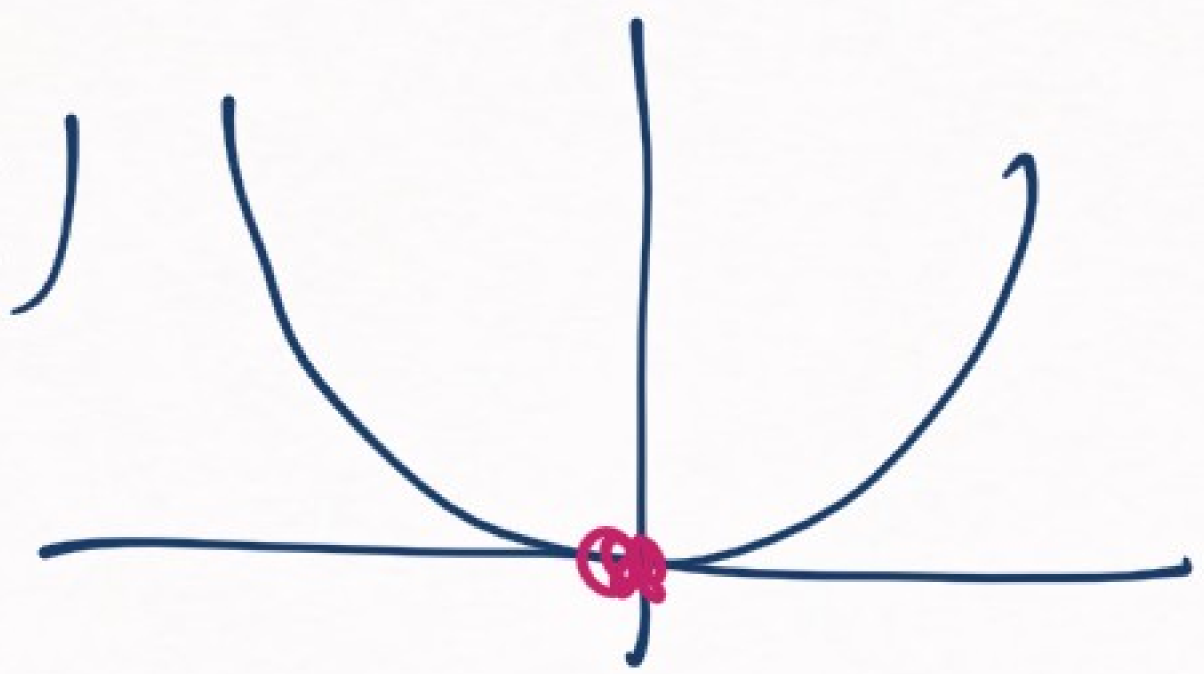
2) Quartic potential for the massive boson

$$V(\phi) = \frac{\mu^2}{2}\sum_i \phi_i^2 + \frac{\lambda}{4}\left(\sum_i \phi_i^2\right)^2$$

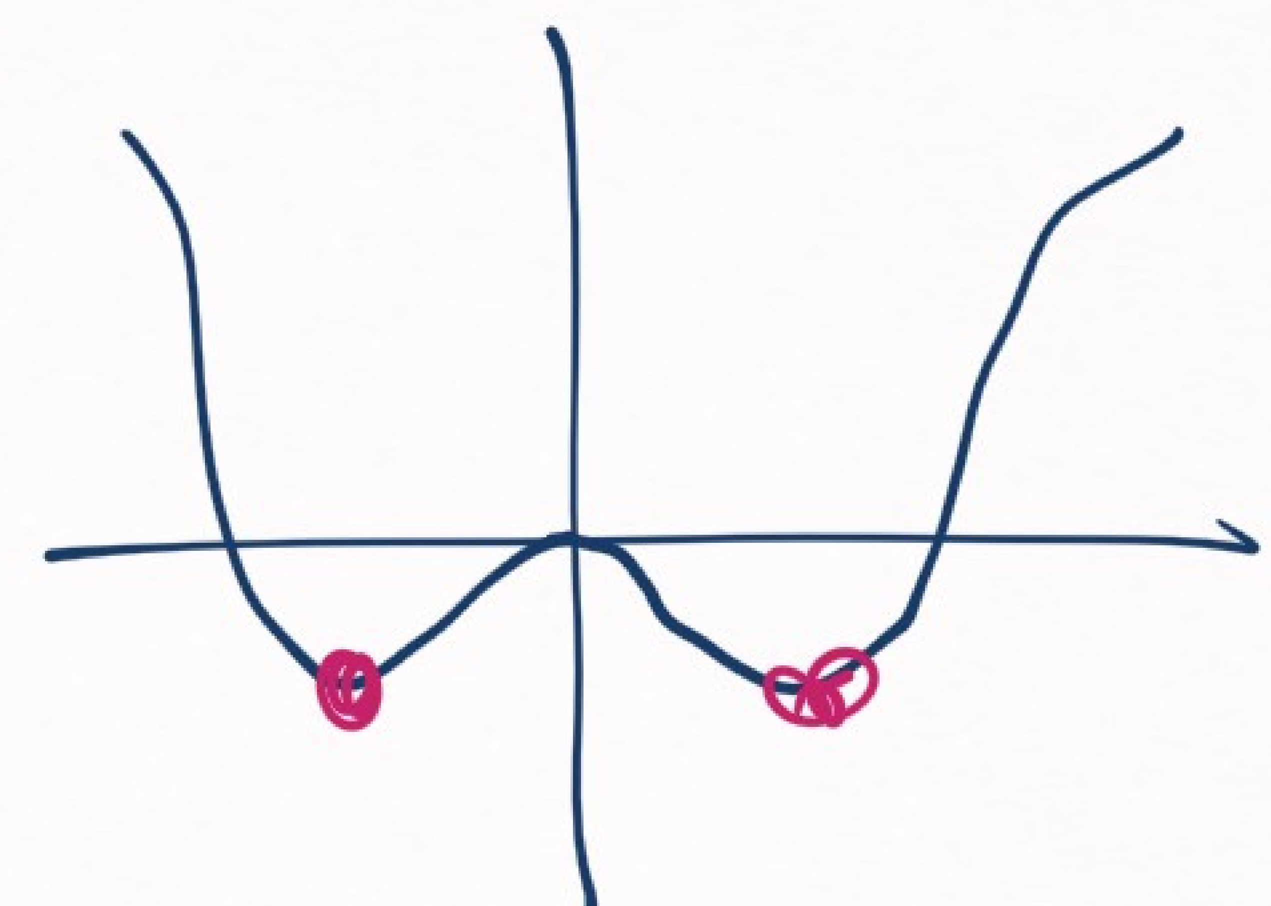
2') Quartic potential is chosen w/ $\mu^2 < 0$

→ $\boxed{\text{MEXICAN HAT POTENTIAL}}$

2)



2'



3) Nature loves to minimize energy

→ choice of ground state

→ Redefinition of the fields

MEXICAN HAT

$$\begin{cases} \phi_i = 0 \text{ not minimum, but } |\vec{\phi}| = v \\ \pi_i = \phi_i - v \ / \ |\vec{\pi}| = 0 \end{cases}$$

corresponds to the minimum

Why? → to be able to solve the QFT

Note → in QFT, what we do is to somehow reduce the problem to a set of infinite harmonic oscillator

Σ (h.o.)

$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}m^2\phi^2 \longrightarrow$ commutators

(→ creation/annihilation operators of h.o.)

4) End result is a theory w/

4.a) massive nucleons

4.b) massless pions

4.c) massive scalar boson (sigma)

→ When LσM was formulated, the σ was not found experimentally

$\Rightarrow$ Formulate the non-linear σ model

(end result similar but wo/sigma)

$\nearrow$

(Later we found out that the sigma indeed exists)

Actually, the LoM is just one particular example of a more general result

$\rightarrow$ GOLDSTONE THEOREM

NAMBU-GOLDSTONE THEOREM

→ full generalization of the idea behind the LσM

→ [SIMPLE DERIVATION]

(not very QFT-ish, but more QM-ish)

(depend on group theory)

1) Hamiltonian H invariant under group G

$$[H, G] = 0$$

2) H has a vacuum state (minimum energy or ground state) $\underline{\underline{|0\rangle}}$

$$H|0\rangle = E_0|0\rangle \ , \quad |0\rangle \text{ ground/vacuum state}$$

3) Sometimes $|0\rangle$ is not invariant under the group G

$[H, G] = 0$ but $\boxed{G|0\rangle \neq |0\rangle}$

What we expect is that $G|0\rangle = e^{i\alpha}|0\rangle$

4) Yes, $|0\rangle$ is invariant under a subgroup of G

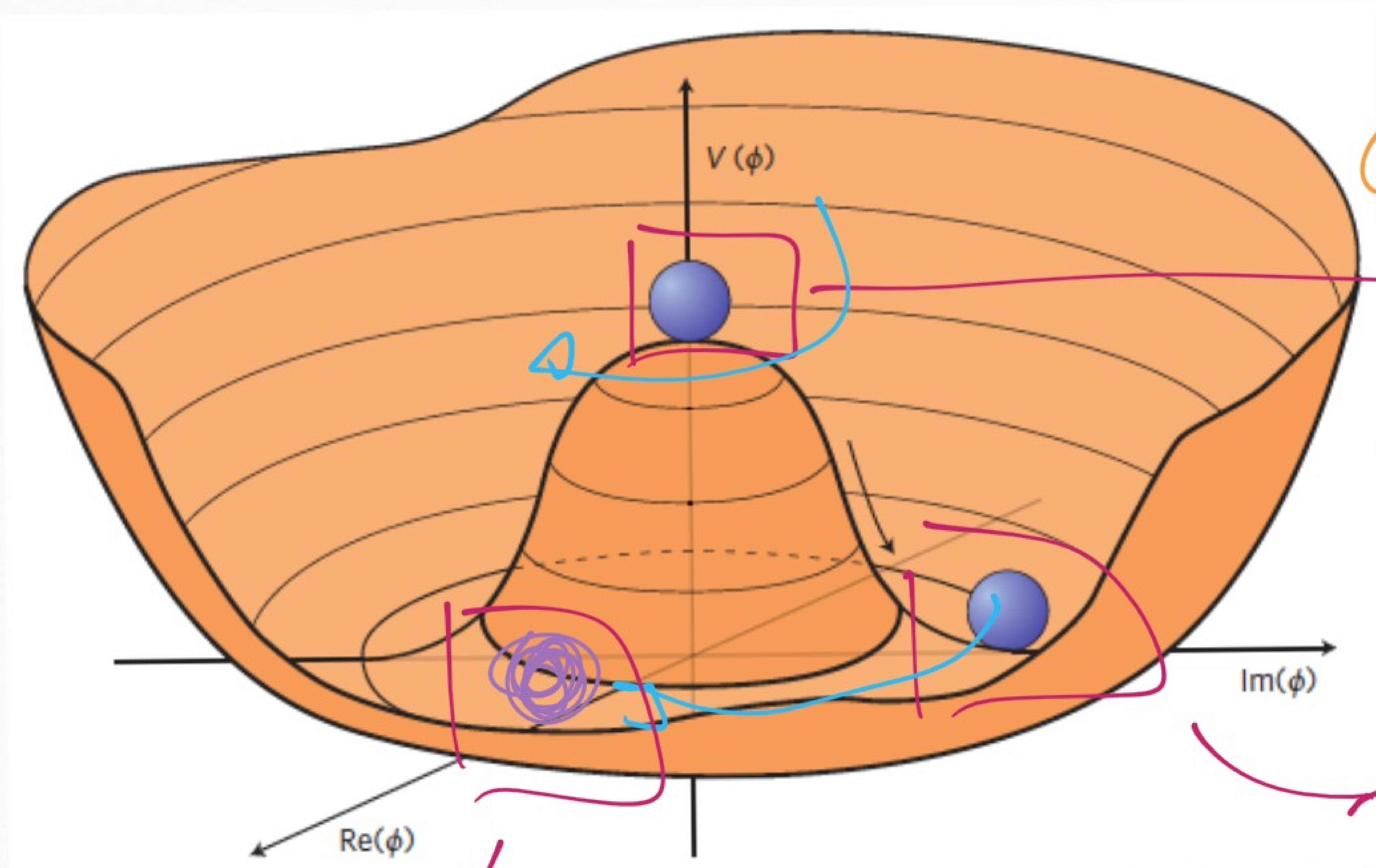
$$F \subseteq G \;/\; F|0\rangle = e^{i\alpha}|0\rangle$$

$$\exists$$

→ let's go to 3)

$G = O(2)$

(rotations on the plane)



(maximum)

$|\phi_1\rangle$

$R|\phi_1\rangle = e^{i\alpha}|\phi_1\rangle$

$|\phi_1'\rangle$ (minimum)

$R|\phi_1'\rangle = |\phi_1''\rangle \rightarrow \oplus$

$|\phi_1''\rangle$?

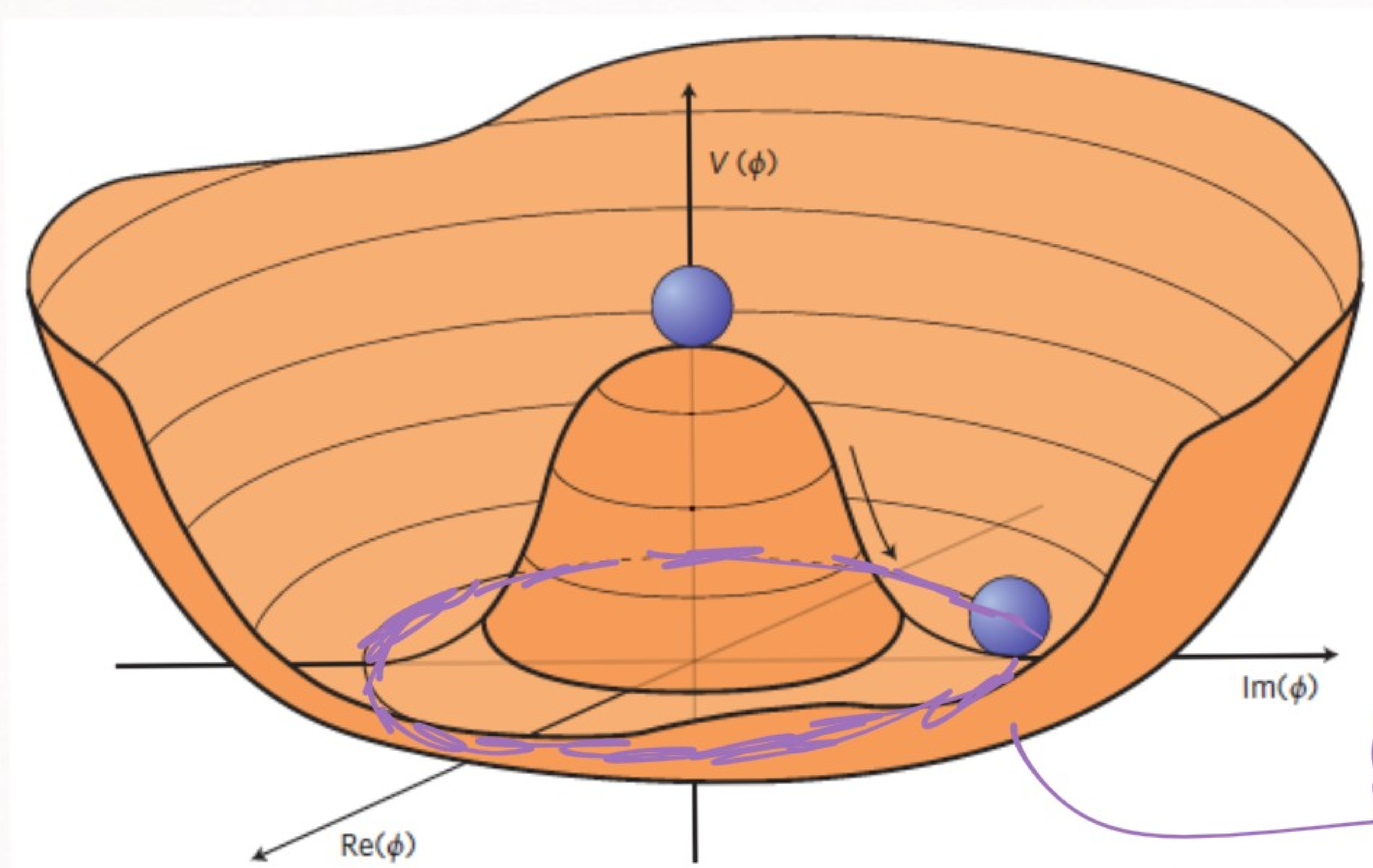
$\circledast \rightarrow R|\phi_1'\rangle \neq |\phi_1'\rangle$

that is, $R|\phi_1'\rangle$ is linearly independent of $|\phi_1'\rangle$

$\Rightarrow$

Vacuum (ground) state not invariant under rotation

In this case, this is because the minumum energy state is not uniqe



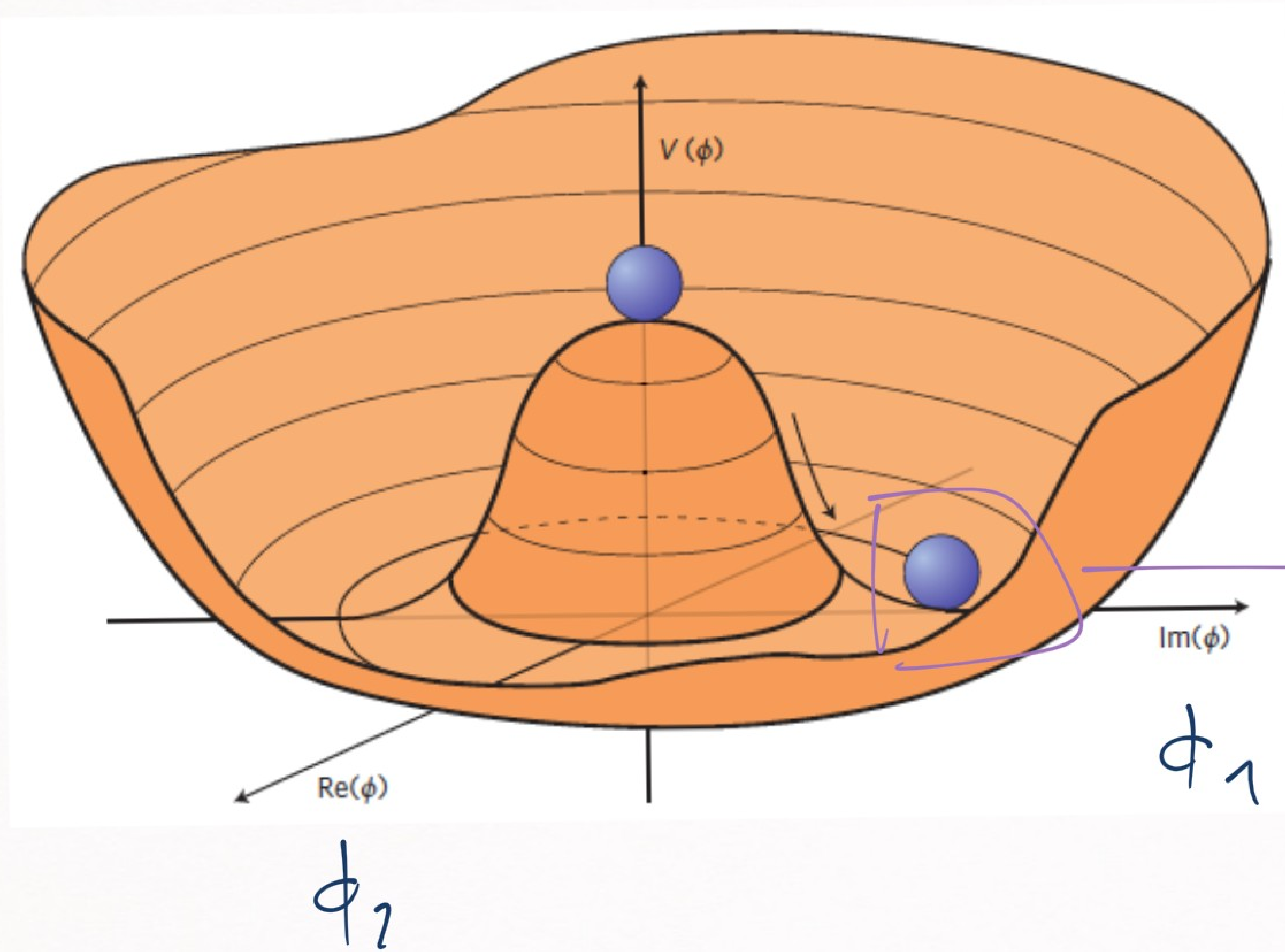
all minima

4) $|0\rangle$ not unique (e.g. because there are may solutions to $H|0\rangle = E_0|0\rangle$)

$|0\rangle, |0'\rangle, |0''\rangle, \ldots$

$|0\rangle$ still invariant under $\underline{\underline{F \subseteq G}}$

(a $\underline{\underline{\text{subgroup}}}$ of G)



$G = O(2)$

or $U(1)$

for $|\phi_1\rangle$ ...

$F =$ trivial group

$(\mathbb{Z}_1, C_1)$

5) If $[H, G] = 0$, $G|0\rangle \neq |0\rangle$

but $F|0\rangle = e^{i\phi}|0\rangle$ (w/ $F \subseteq G$)

$\Rightarrow$ There will be a series of massless fields in the theory

Their number will be

$n_G - n_F$

(here is the only time we have use QFT)

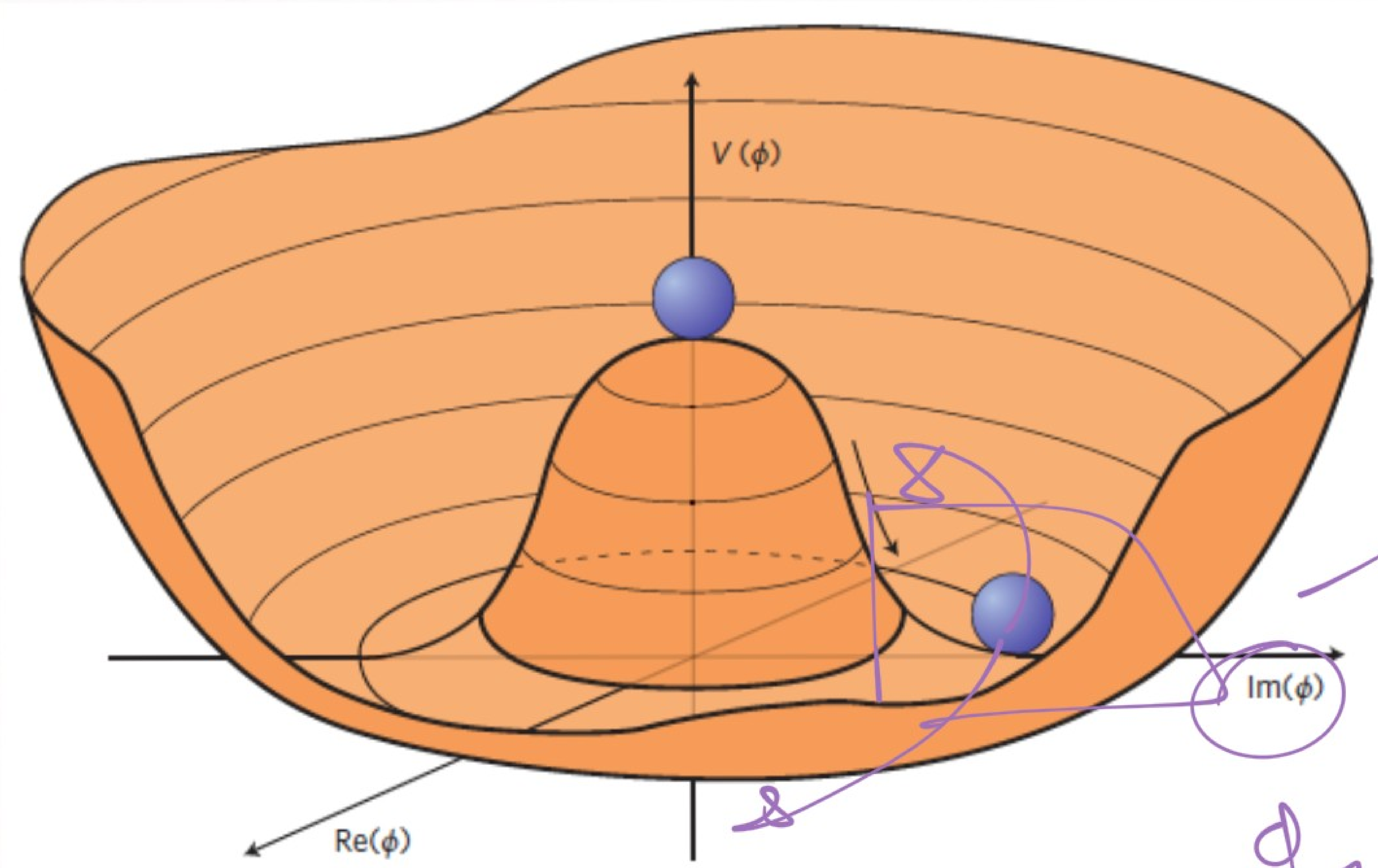
→ # of massless fields $= n_G - n_F$

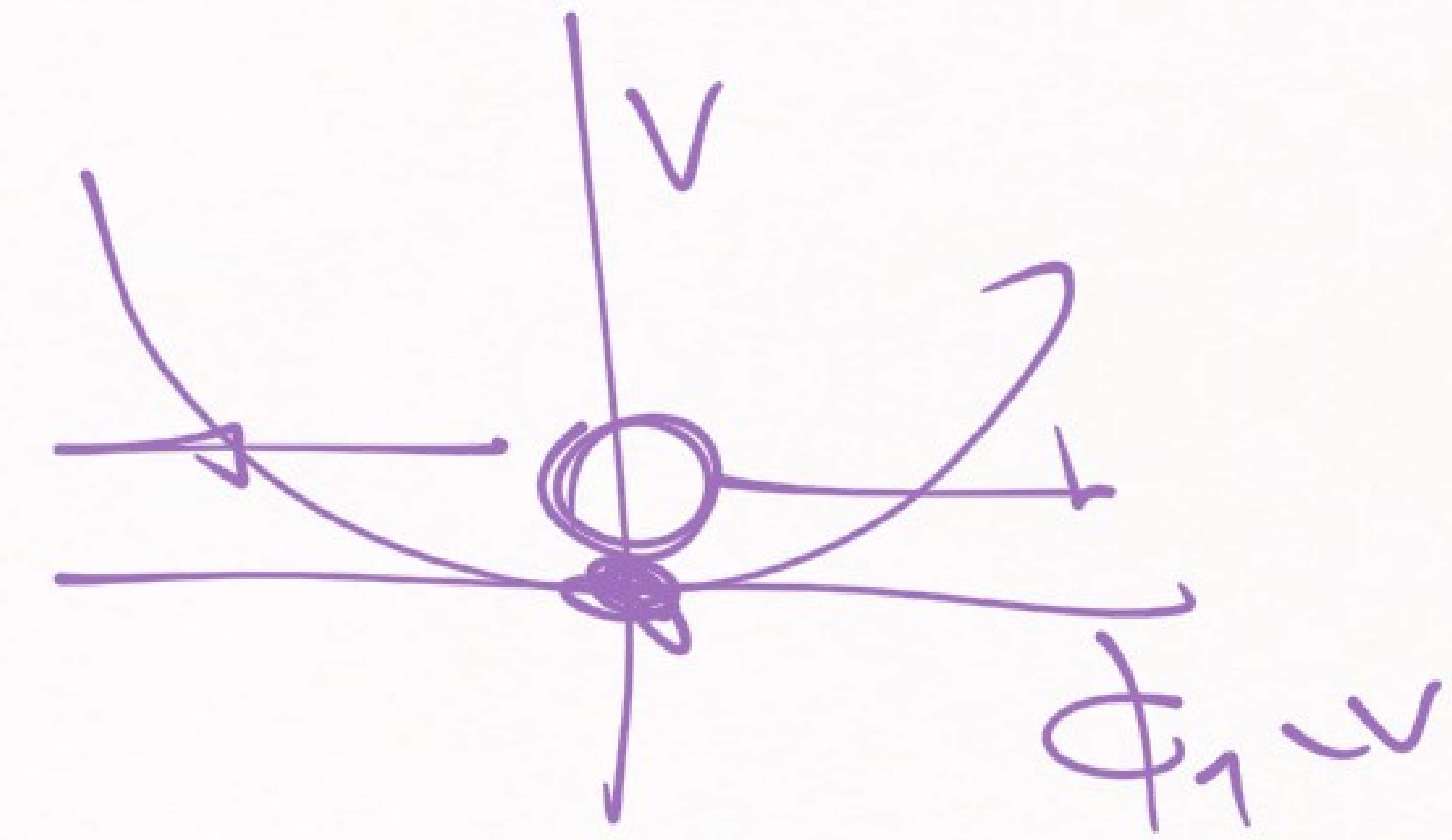
$\#$ of generators of group G

$\#$ of generators of group F

representation theory

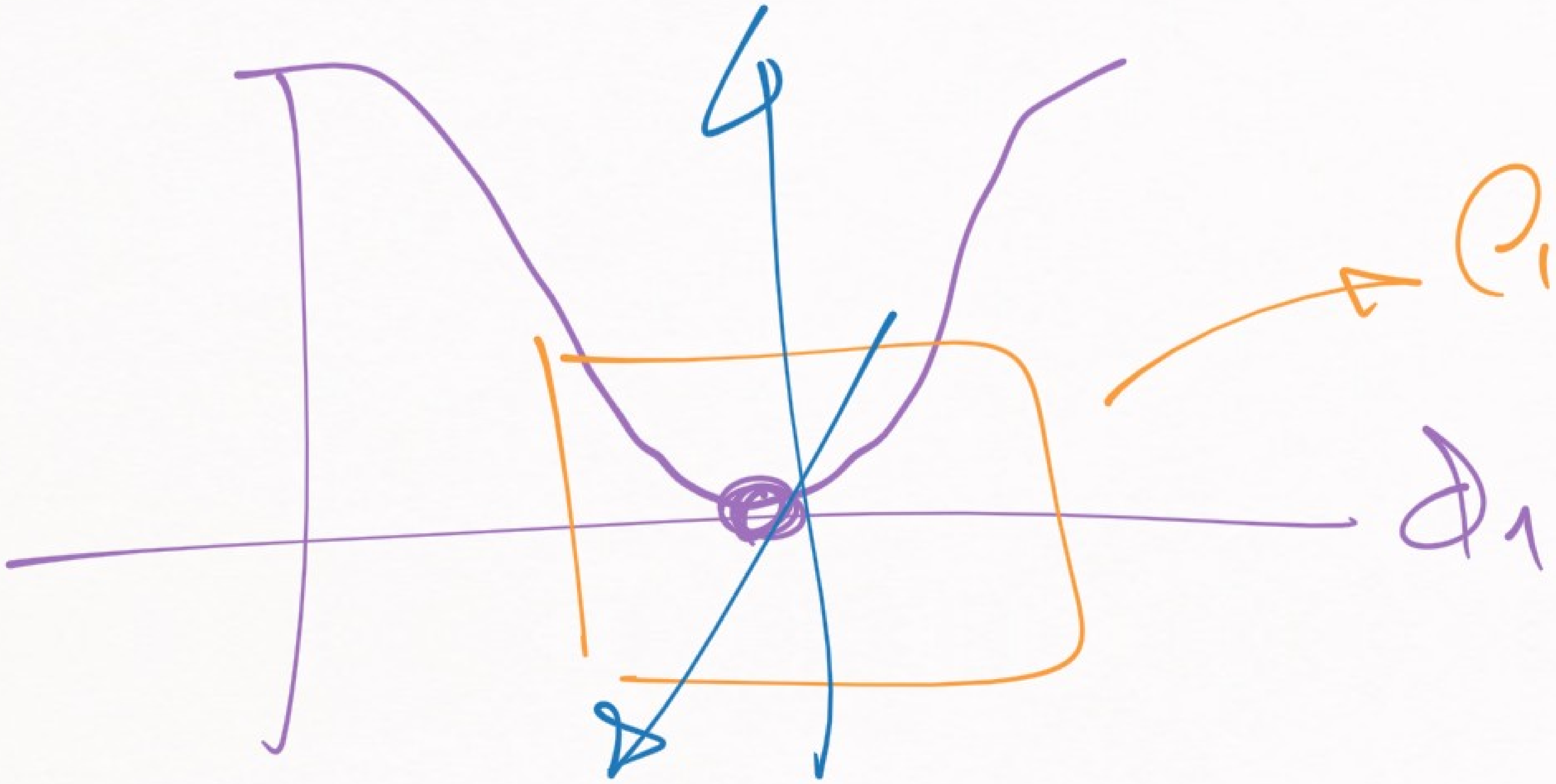
$\boxed{\text{QFT}}$ → we reduce everything to harmonic oscillator





potential

$\propto (\phi_1 - v)^2$

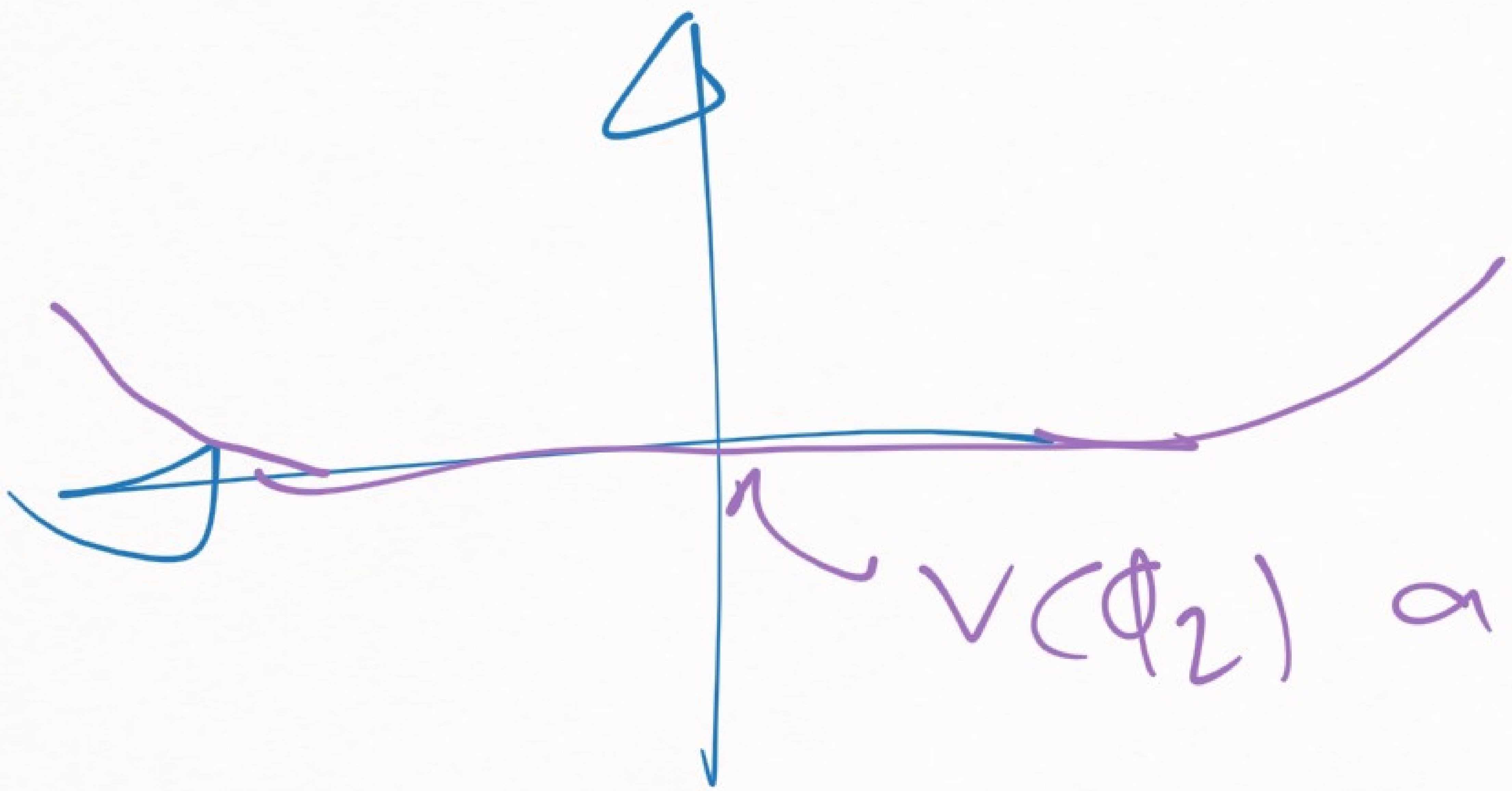


like h.o. potential

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}m^2\phi^2$$

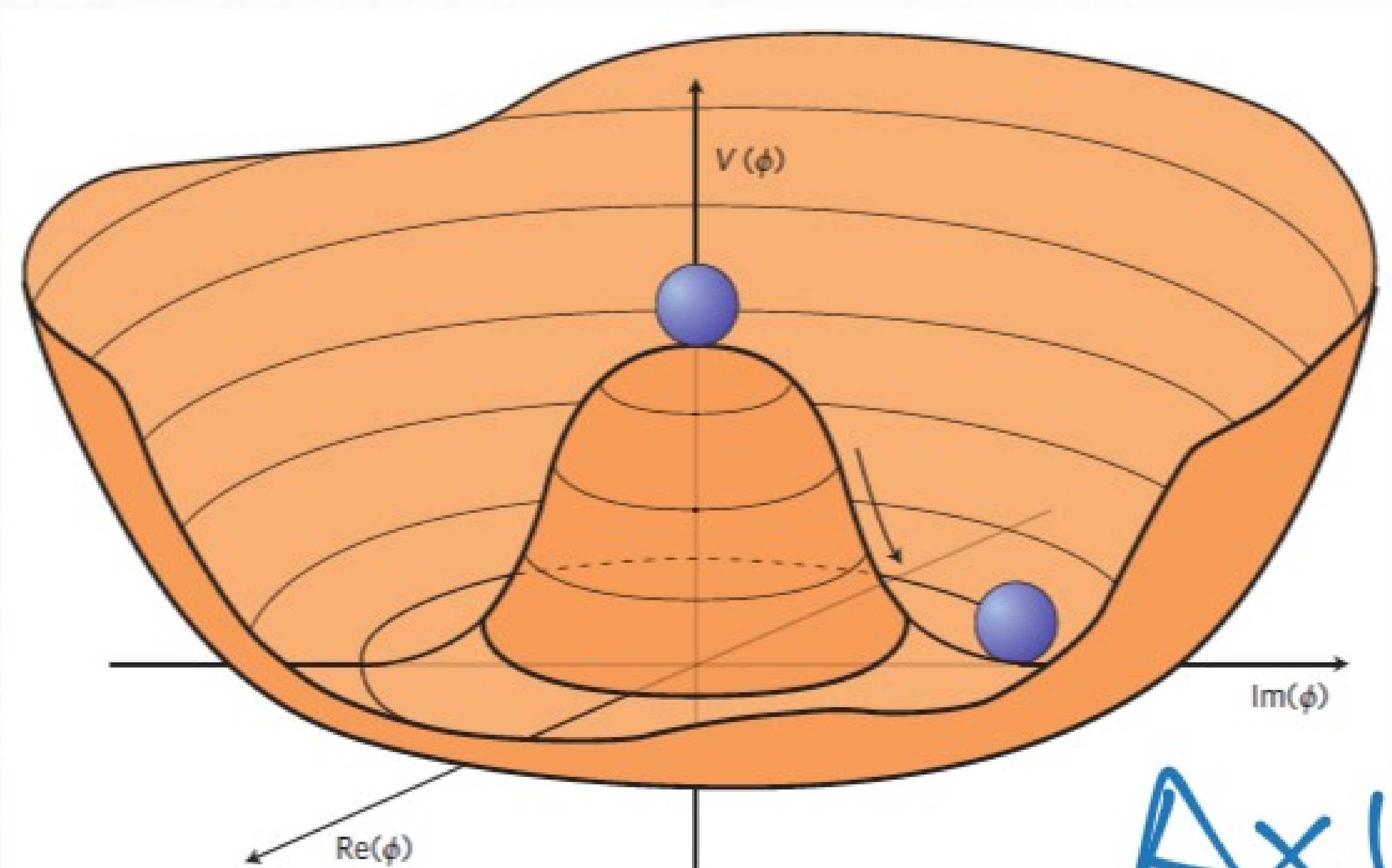
quadratic potential

$\simeq$ mass



$V(\phi_2)$ around here $\simeq 0$

$|\phi_1\rangle$ here can be excited in two ways



Axis 1

Axis 2

1) around axis 1

→ the excitation will be massive

2) around axis 2

→ the excitation will be massless

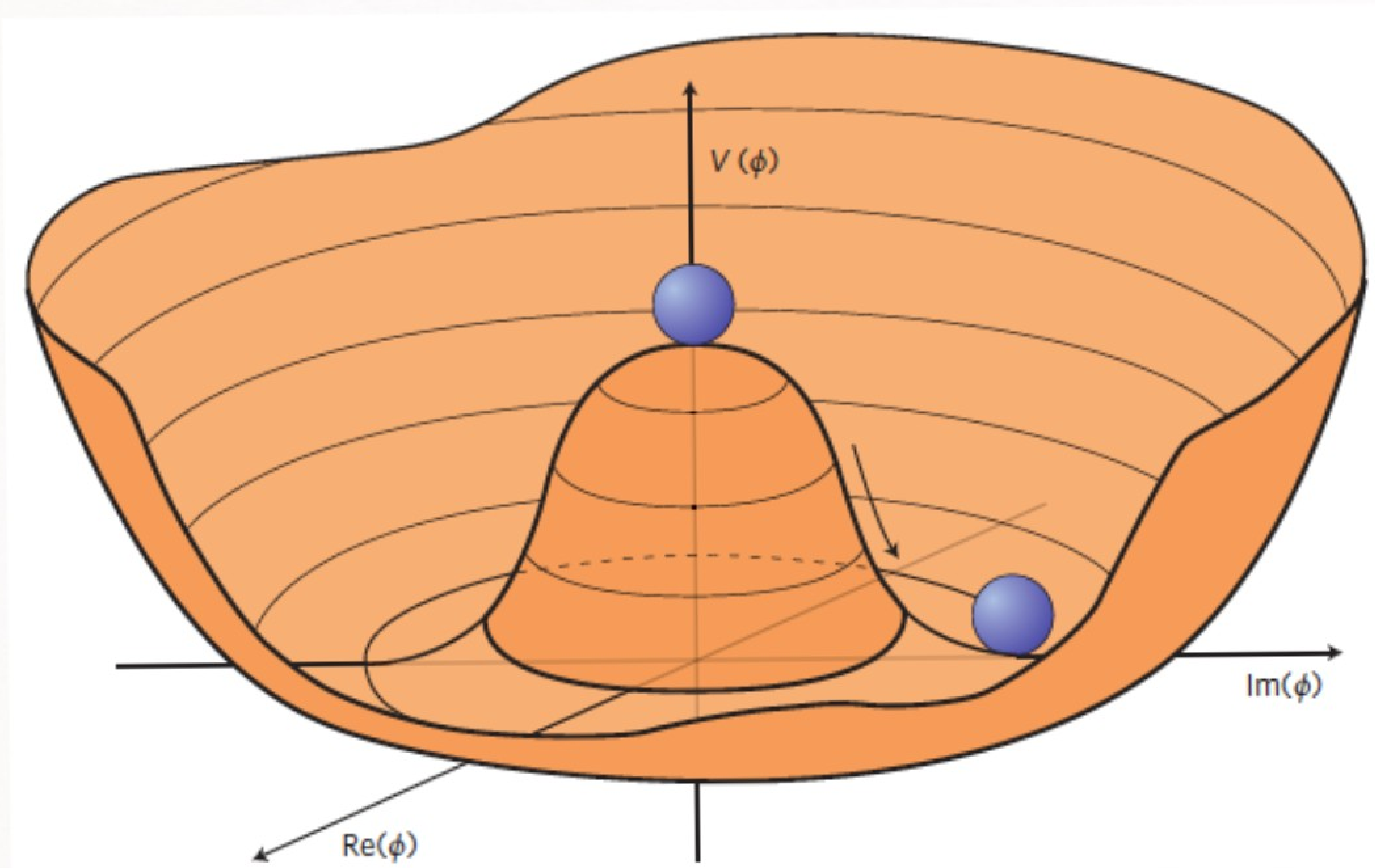
Goldstone theorem

→ Excitations around "axis 2" correspond to the massless bosons in Goldstone theorem

[$n_G - n_H$ massless bosons fields]

$G = O(2)$

$F = Z_1 / C_1 / SO(1)$ → (Group theory tells us)



$G = O(n)$

$n_G = \frac{n(n-1)}{2}$

$G = \text{trivial}$

$n_G = 0$

→ In the previous case

$n_G = 1$
$n_F = 0$

$G = O(2)$

$F = SO(1) / \mathbb{Z}_1 / \ldots$
(trivial group)

$n_G - n_F$ massless fields

↓

1 massless field
(correct)

$\boxed{\text{SECOND EXAMPLE}} \longrightarrow \boxed{\text{LGM}}$

$$V(\phi) = \frac{\mu^2}{2}\sum_{i=0}^{3}(\phi_i^2) + \frac{\lambda}{4}\left(\sum_{i=0}^{3}\phi_i^2\right)^2$$

$\boxed{G = O(4)}$ (if we assume $\phi_0, \phi_1, \phi_2, \phi_3$ real)

for $\mu^2 < 0 \Rightarrow \boxed{F = O(3)} \longrightarrow$ Let's check this

Vacuum in LSM was $|0\rangle = \{ \phi_0 = v \}$

$\{ \phi_0, \vec{\phi} \}$ $\quad |\vec{\phi}^{\,2}| = 0$

$$\boxed{F = O(3)}$$

$\Rightarrow$ We count the generators:

$$G = O(4) \to n_G = \frac{n(n-1)}{2} = 6$$

$$F = O(3) \to n_F = \frac{n(n-1)}{2} = 3$$

$\Rightarrow$ $n_G - n_F = 3$ $\underline{\text{massless fields}}$

$\Rightarrow \quad \alpha_i \ , \ i = 1,2,3 \ \Rightarrow \ \vec{\pi}$

$\Rightarrow$ GOLDSTONE THEOREM

explains the findings of the LσM

Application → $\boxed{\text{CHIRAL SYMMETRY}}$

↝ We already said a bit about this symmetry

⊗ → derivative interaction

(e.g. the correct pion interaction

was $\mathcal{L} = \frac{g_A}{2f_\pi} \bar{\psi}_N \gamma_5 \gamma^\mu \vec{\tau} \cdot \partial_\mu \vec{\pi}\, \psi_N$)

Quarks → u, d, s

(especial)

$m_q \simeq 0$

$\frac{m_u}{\Lambda_{QCD}}, \frac{m_d}{\Lambda_{QCD}}, \frac{m_s}{\Lambda_{QCD}} < 1$

CHIRAL SYMMETRY

SPONTANEOUSLY BROKEN

We can apply GOLDSTONE THEOREM

What is $\boxed{\text{CHIRAL SYMMETRY}}$?

Quantum mechanical analog of chiral symmetry

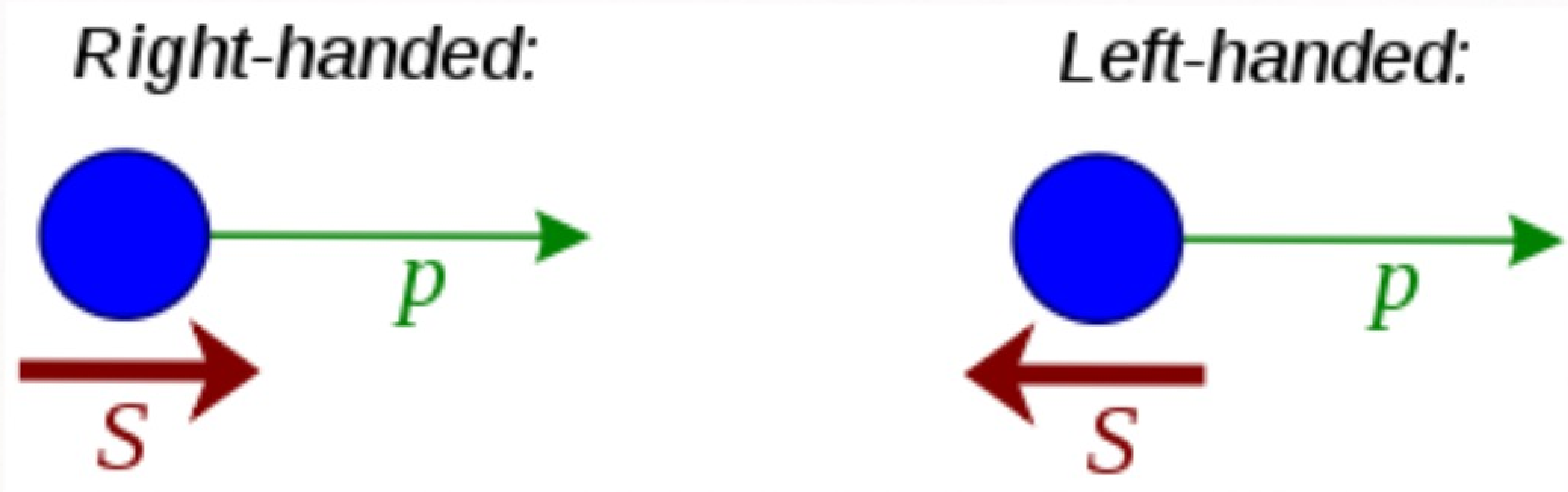
$\boxed{\text{Helicity}}$ → Will help us understand this chiral symmetry

1) Helicity $\rightarrow$ $\lambda = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$ (for spin-$1/2$ in this example)

two eigenvalues $\boxed{\lambda = \pm 1}$

$\lambda = +1$

$\lambda = -1$



$\lambda = +1$

(Right handed)

$\lambda = -1$

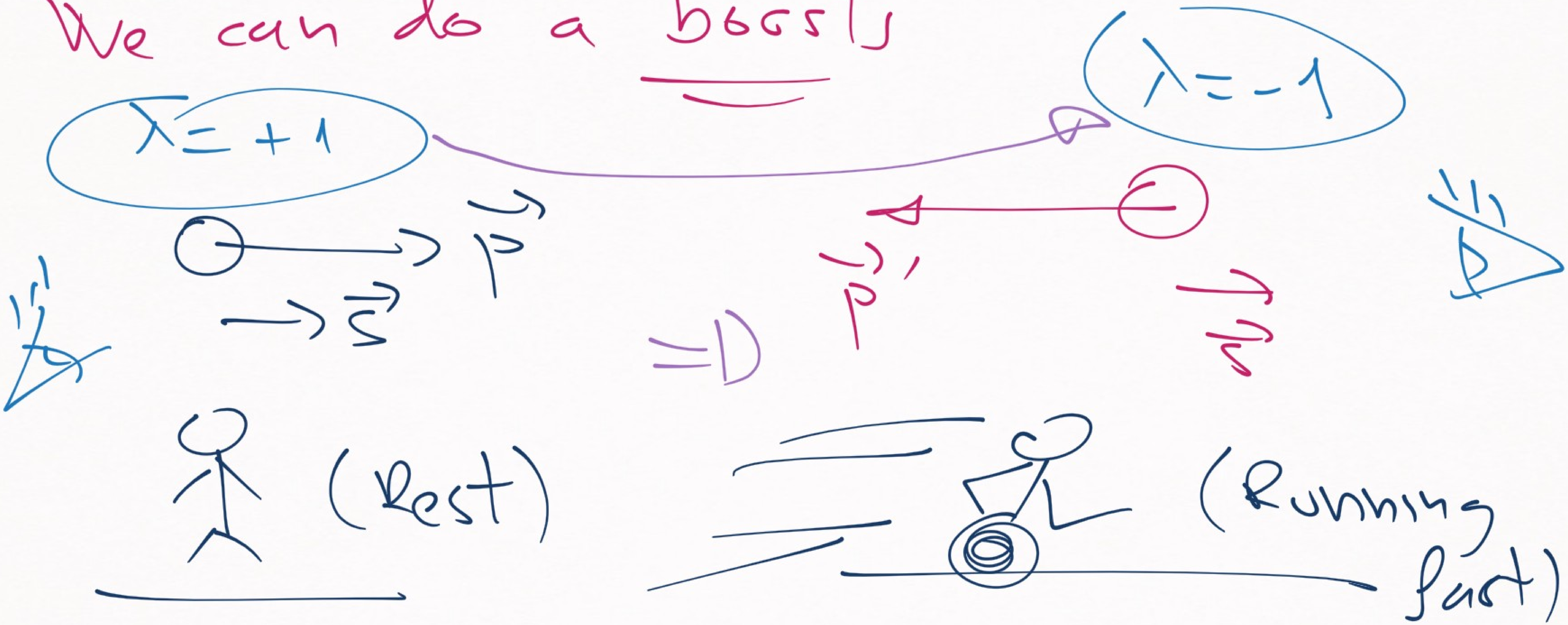
(Left handed)

For $m \neq 0$, helicity is not a conserved quantity

Why →

→ Why λ not conserved for $m \neq 0$

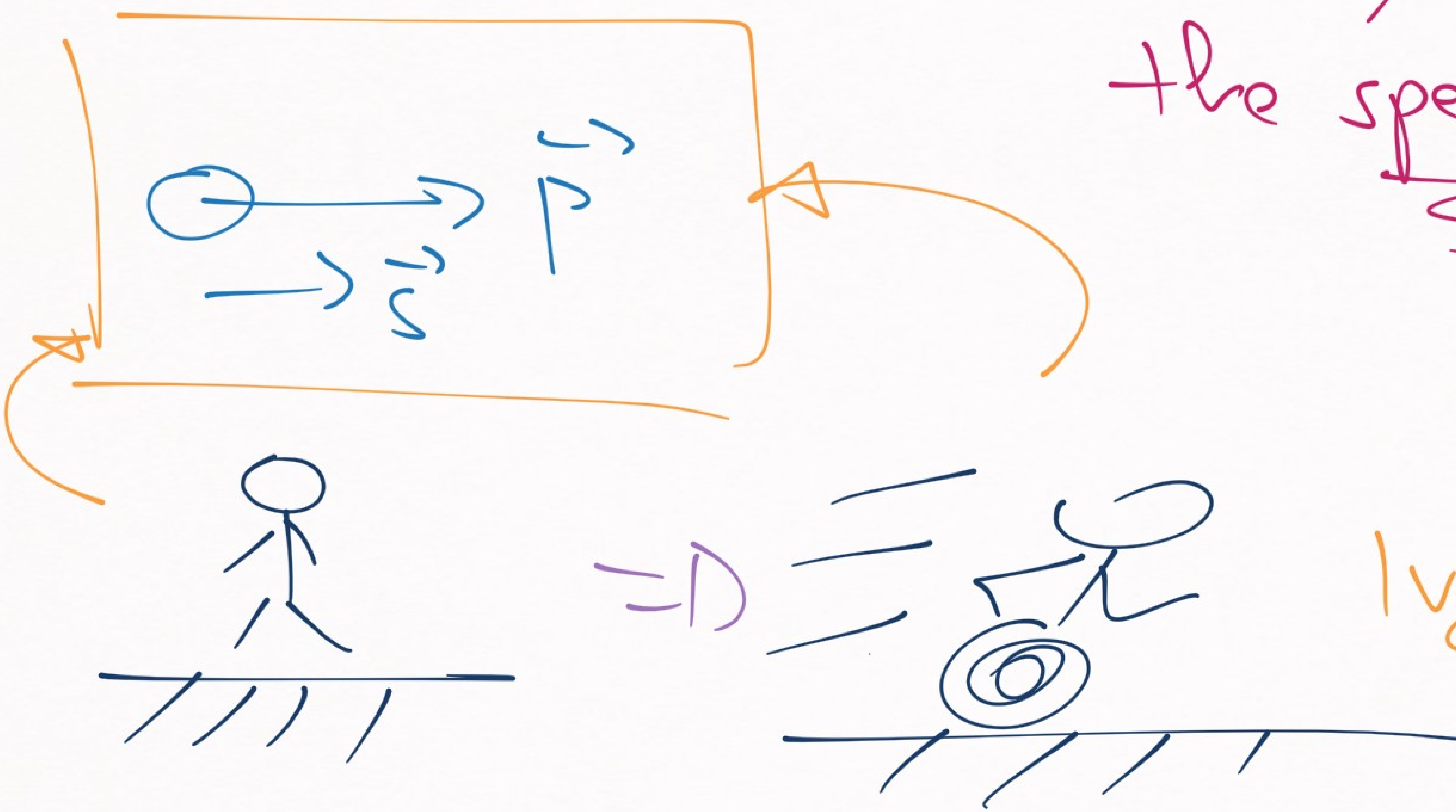
We can do a boost



If $m \neq 0 \Rightarrow$ $\lambda = +1$ can become $\lambda = -1$
depending on the choice
of frame of reference
(boosted / non-boosted)

$\rightarrow$ $\boxed{\text{not true if } m = 0}$

If $m = 0 \Rightarrow \boxed{v = 1}$ the particle will always travel at the speed of light



$|v_{ours}| < 1$

$\left(\frac{v}{c}\right)$

massless particles $\longrightarrow$ helicity is conserved

(except for parity)

[The QFT analog of helicity]

$$\mathcal{L} = \bar{\Psi}(\underbrace{i\not{\partial}}_{\text{kinetic term}} - \underbrace{m}_{\text{mass term}})\Psi \longrightarrow \boxed{\text{Dirac field}}$$

$$\Downarrow$$

$$\boxed{\exists \text{ global } U(1) \text{ symmetry}}$$

Global symmetry $\to$ $\boxed{U(1) \text{ symmetry}}$

$$\left.\begin{aligned} \psi(x) &\to e^{i\alpha}\psi(x) \\ \psi^\dagger(x) &\to e^{-i\alpha}\psi^\dagger(x) \end{aligned}\right\} \mathcal{L} \to \mathcal{L}$$

$$\bar{\psi}\psi = \psi^\dagger \gamma^0 \psi \to \psi^\dagger \gamma^0 \psi$$

→ there might be more symmetries here

why? → $\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$ → four components

→ further differentiation of this field:

$\psi = \psi_L + \psi_R$

$\psi_L = P_L \psi = \frac{1}{2}(1 - \gamma_5)\psi$

$\psi_R = P_R \psi = \frac{1}{2}(1 + \gamma_5)\psi$

$$\boxed{\begin{aligned} \psi &= \psi_L + \psi_R \\ \psi_L &= P_L \psi = \frac{1-\gamma_5}{2}\psi \\ \psi_R &= P_R \psi = \frac{1+\gamma_5}{2}\psi \end{aligned}} \longrightarrow \boxed{\begin{aligned} P_L^2 &= P_L \\ P_R^2 &= P_R \\ P_L^\dagger &= P_L \\ P_R^\dagger &= P_R \end{aligned}}$$

$\psi_L \rightarrow$ left-handed Dirac field.

$\psi_R \rightarrow$ right-handed

$\rightarrow$ they are projectors

$(P_L + P_R = 1)$

$\psi = \psi_L + \psi_R$ → this separation is possible

extra symmetries? (maybe)

$\psi_L \to e^{i\alpha_L} \psi_L$

$\psi_R \to e^{i\alpha_R} \psi_L$

Is it a symmetry?

analogous to

$\psi \to e^{i\alpha} \psi$

$$\psi_L \to e^{i\alpha_L}\psi_L \Rightarrow U_L(1)$$

$$\psi_R \to e^{i\alpha_R}\psi_R \Rightarrow U_R(1)$$

$\boxed{\text{DO THEY WORK?}}$

(it depends)

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\cancel{\partial} - m)\psi \\ &= \bar{\psi}\, i\cancel{\partial}\psi \quad \Big\}\ \text{kinetic \&} \\ &\quad - m\bar{\psi}\psi \quad \Big\}\ \text{mass}\end{aligned}$$

$\underline{\underline{\text{terms}}}$

(1) Kinetic

$$\bar{\psi}\not{\partial}\psi = \bar{\psi}_L\not{\partial}\psi_L + \bar{\psi}_R\not{\partial}\psi_R$$

$$\xrightarrow{U_L} \bar{\psi}_L\not{\partial}\psi_L + \bar{\psi}_R\not{\partial}\psi_R$$

$$\xrightarrow[U_R]{} \bar{\psi}_L\not{\partial}\psi_L + \bar{\psi}_R\not{\partial}\psi_R$$

→ kinetic term has both $U_L(1)$ & $U_R(1)$ symmetry

② mass term

$$m\bar{\psi}\psi = m\bar{\psi}_L\psi_R + m\bar{\psi}_R\psi_L$$ (mixes L & R terms)

$$\xrightarrow[U_1(L)]{} me^{-i\alpha_L}\bar{\psi}_L\psi_R + me^{i\alpha_L}\bar{\psi}_R\psi_L$$

$$\xrightarrow[U_1(R)]{} me^{i\alpha_R}\bar{\psi}_L\psi_R + me^{-i\alpha_R}\bar{\psi}_R\psi_L$$

$$\bar{\psi}\psi \;\cancel{\longrightarrow}\; \bar{\psi}\psi$$

$$U_L(1),\ U_R(1)$$

not invariant under these two transformations

3

1) $\mathcal{L}_{Dirac}$, $m \neq 0$

$\rightarrow$ Global symmetry is $U_{\underline{L+R}}(1)$

$$\psi = \underline{\psi_L + \psi_R}, \quad \psi \to e^{i\alpha}\psi$$

2) $\mathcal{L}_{Dirac}$, $m = 0$

CHIRAL SYMMETRY

$\rightarrow$ Global symmetries are $\boxed{U_L(1), U_R(1)}$

How does chiral symmetry apply to $\boxed{\text{QCD?}}$

$$\mathcal{L}_{QCD} = \underbrace{-\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}}_{\text{Gluons (not important for the moment)}} + \underbrace{\bar{q}\, i \not{D}\, q}_{\text{quark kinetic}} - \underbrace{\bar{q} \mathcal{M} q}_{\text{quark mass}}$$

terms

$$q = \begin{pmatrix} u \\ d \\ s \\ c \\ b \\ t \end{pmatrix}, \quad \mathcal{M} = \begin{pmatrix} m_u & & & & & \\ & m_d & & & 0 & \\ & & m_s & & & \\ & & & m_c & & \\ & 0 & & & m_b & \\ & & & & & m_t \end{pmatrix}$$

Question $\rightarrow$ can we ignore a few of these masses?

(e.g. by considering them as perturbations)

→ in certain casses we can approximate

$$\boxed{m_q \simeq 0}$$

↳ this has to do w/ QCD natural scale

comparison

$$\left[\Lambda_{QCD} \simeq (200-350)\,\mathrm{MeV}\right]$$

$$u, d, s, c, b, t$$

1) $\dfrac{m_u}{\Lambda_{QCD}}, \dfrac{m_d}{\Lambda_{QCD}} \ll 1 \quad \left(\dfrac{m_s}{\Lambda_{QCD}} < 1\right)$ ✓

u, d (& maybe s) quarks $\rightarrow$ $m_u, m_d \simeq 0$ $(m_s \simeq 0)$

2) $\dfrac{m_c}{\Lambda_{QCD}}, \dfrac{m_b}{\Lambda_{QCD}}, \dfrac{m_t}{\Lambda_{QCD}} \gg 1$ ✗

$\boxed{\text{Reminder}}$

$$\left.\begin{array}{l} m_u \sim 2\,\text{MeV} \\ m_d \sim 5\,\text{MeV} \\ m_s \sim 95\,\text{MeV} \end{array}\right] \longrightarrow \text{chiral symmetry might be applicable}$$

$$\left.\begin{array}{l} m_c \sim 1.2\,\text{GeV} \\ m_b \sim 4.2\,\text{GeV} \end{array}\right) \longrightarrow \text{but not for these quarks}$$

QCD $\rightarrow$ $\underbrace{\text{light quarks}}_{\text{chiral symmetry}}$ & $\underbrace{\text{heavy quarks}}_{\text{other symmetries (heavy quark symmetry)}}$

two approximations

a) u, d light $\rightarrow$ $n = 2$

b) u, d, s light $\rightarrow$ $n = 3$

a) $m_q = 0 \longrightarrow$ chiral transformations

U_L & U_R

1-type of fermion field $\begin{cases} \psi_L \to e^{i\alpha_L}\psi_L \\ \psi_R \to e^{i\alpha_R}\psi_R \end{cases}$

2-types of fermion fields $\Rightarrow \psi_{L/R} \to \begin{pmatrix} u \\ d \end{pmatrix}_{L/R}$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \rightarrow (2\times 2 \text{ matrix}) \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_R \rightarrow \underbrace{(2\times 2 \text{ matrix})}_{\text{what type of matrix}} \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$(\bar{u} \ \bar{d})_L \begin{pmatrix} u \\ d \end{pmatrix}_L \rightarrow (\bar{u} \ \bar{d})_L \begin{pmatrix} u \\ d \end{pmatrix}_L$$

Since u, d are complex

$\Rightarrow$ 2×2 matrices need to belong to $\underline{U(2)}$

$U_L(2)$

$U_R(2)$

Σ

$$\begin{pmatrix} u \\ d \end{pmatrix}_{L/R} \to V_{L/R} \begin{pmatrix} u \\ d \end{pmatrix}_{L/R}$$

$$\left.\begin{aligned} V_L &\in U_L(2) \\ V_R &\in U_R(2) \end{aligned}\right\} U_L(2) \otimes U_R(2) \text{ chiral symmetry}$$

$$\boxed{\begin{aligned} q_L &\to V_L q_L \\ q_R &\to V_R q_R \end{aligned}}$$

b) if we add s:

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}_{L/R} \longrightarrow V_{L/R} \begin{pmatrix} u \\ d \\ s \end{pmatrix}_{L,R}$$

$V_L \in U_L(3)$

$V_R \in U_R(3)$

$\Rightarrow$ symmetry group for n types of light quarks

$$\boxed{G = U_L(n) \otimes U_R(n)}$$

Result 1) For n species of light quarks

$\mathcal{L}_{QCD}$ invariant $G = U_L(n) \otimes U_R(n)$

except that this is not true

(something unexpected happens)

$\longrightarrow$ $\boxed{\text{chiral anomaly}}$

RECAP $\rightarrow$ anomaly is a classical symmetry broken by the quantization process

CHIRAL ANOMALY $\rightarrow$ $U_{L-R}(1)$ will be violated

$$g_L \to e^{i\alpha_L} g_L$$

$$g_R \to e^{i\alpha_R} g_R$$

$g_L - g_R$

$\nRightarrow e^{i\alpha_{L-R}}(g_L - g_R)$

(if $n > 1$)

Result 1')

$$G = U_L(n) \otimes U_R(n)$$

$$\Big\downarrow \text{ chiral anomaly on } U_{L-R}(1)$$

$$G = \underline{SU_L(n)} \otimes SU_R(n) \otimes U_{L+R}(n)$$

$g_L \to V_L g_L$ $\qquad$ $g_R \to V_R g_R$ $\qquad$ $g \to e^{i\alpha} g$

$V_L \in SU_L(n)$ $\qquad$ $V_R \in SU_R(n)$

[Confront this w/ reality]

$$G = SU_L(n) \otimes SU_R(n) \otimes U_{L+R}(1)$$

$\boxed{\text{Prediction}}$

$$\boxed{m(H, J^+) = m(H, J^-)}$$

meson

$q\bar{q} \to$ $q \, \mathcal{O}_J \, \bar{q}$, $q \, \mathcal{O}_J \, \gamma_5 \, \bar{q}$ $\to$ opposite parities (Jr)

$H \to$ hadron

What happens is :

1) LoM $\rightarrow$ $m_\pi(0^-) \simeq 140\,\text{MeV}$

$m_\sigma(0^+) \simeq 500\,\text{MeV}$ $\qquad m_\sigma \neq m_\pi$

2) $N(940)$, $N^*(1535)$ $\qquad m_N \neq m_{N^*}$

$J = 1/2^+ \qquad 1/2^-$

3) $\rho(770)$, $a_1(1260)$ $\qquad m_\rho \neq m_{a_1}$

$J = 1^- \qquad J = 1^+$

→ GROUND STATE OF QCD IS NOT INVARIANT UNDER

$$G = SU_L(n) \otimes SU_R(n) \otimes U(1)_{L+R}$$

Why? → positive & negative parity states have different masses

$\underline{\ne}$

F ←

$\rightsquigarrow$ Opportunity to use GOLDSTONE THEOREM

RECAP

H / $[H, G] = 0$

$|0\rangle$ / $G|0\rangle \neq |0\rangle$

but still $F \subseteq G$

$F|0\rangle = ()|0\rangle$

$\boxed{QCD}$

$G = SU_L(n) \otimes SU_R(n) \otimes U(1)_{L+R}$

$G|mn\rangle \to |m\tilde{n}\rangle$

not vacuum

What is the symmetry of the lower mass hadrons?

1^- $\quad$ 1^+

$m(\rho) < m(a_1)$

$$\boxed{F = SU_{L+R}(n) \otimes U(1)_{L+R}(n) = U_{L+R}(n)}$$

$1^- \to \underline{\underline{L+R}}$ $\bar{q}\gamma_\mu q$

$1^+ \to L-R$ $\bar{q}\gamma_\mu\gamma_5 q$

$\boxed{\text{GOLDSTONE THEOREM}}$

1) $G = SU_L(n) \otimes SU_R(n) \otimes \underset{L+R}{U(1)}$

$SU(n) \to n^2 - 1$ generators

$n_G = 2n^2 - 1$

2) $F = U_{L+R}(n)$

$U(n) \to n^2$ generators

$n_F = n^2$

3+71 $\longrightarrow$ $\boxed{n^2 - 1 \text{ massless bosons}}$

(they will not be massless once we include $\bar{q} M q$ as a perturbation)

a) $n=2$ chiral symmetry (u,d)

$\rightarrow n^2-1=3$ massless bosons

$\rightarrow$ pions $(m_{\pi^\pm}, m_{\pi} \simeq 140\,\mathrm{MeV})$

J^P?

$\frac{G}{H} \sim SU_{L-R}(n)$

$\bar{q}\gamma_5 q \rightarrow 0^{-}$ $\rightarrow$ pseudoscalars

b) $n=3 \rightarrow n^2-1 = 8$ "massless" bosons

$$\rightarrow \underbrace{\pi^\pm, \pi}_{3}, \underbrace{K^\pm, K^0, \bar{K}^0}_{4}, \underbrace{\eta}_{1}$$

0^- $\qquad$ 0^+

$m_\pi \ll m_\sigma$

$m_K \ll m_{K^0}$

$m_\eta \ll m_{a_0}$

$m_K \simeq 495$ MeV

$m_\eta = 550$ MeV

Σ

By applying the $\boxed{\text{GOLDSTONE THEOREM}}$

$\rightarrow n^2-1$ $\underbrace{\text{massless}}_{m_u,\, m_d,\, m_s \to 0}$ bosons

$\bar{q} M q$ is a perturbation

$\rightarrow$ explains why pions are so light

Second consequence of $\boxed{\text{GOLDSTONE THEOREM}}$

(not really explained why here)

pion interactions are derivative

w/o chiral symmetry :

$$\mathcal{L}_{\pi NN} = g_{\pi NN} \bar{\psi}_N i\gamma_5 \vec{\tau} \cdot \vec{\pi}\, \psi_N$$

(no derivatives)

forbidden

w/ chiral symmetry

allowed

$$\mathcal{L}_{\pi NN} = \frac{g_A}{2f_\pi} \bar{\psi}_N \gamma^5 \gamma_\mu \vec{\tau} \cdot \partial_\mu \vec{\pi}\, \psi_N$$

→ changes the nature of pion interaction

$$\frac{g_A}{f_\pi} = \frac{g_{\pi NN}}{M_N}$$ → Goldberger-Treiman relation

→ pion interactions will be weaker at low energies

→ important for calculation of two-pion exchange potential

(w/o chiral symmetry & derivative interactions, these calculations fail)

WE CONTINUE

ON FRIDAY